

# Probing light-quark Yukawa couplings via hadronic event shapes at lepton colliders

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We propose a novel idea for probing the Higgs boson couplings through the measurement of hadronic event shape distributions in the decay of the Higgs boson at lepton colliders. The method provides a unique test of the Higgs boson couplings and of QCD effects in the decay of the Higgs boson. It can be used to directly probe the Yukawa couplings of the light quarks and to further test the mechanism of electroweak symmetry breaking. From a case study for the proposed Circular Electron-Positron Collider, light-quark couplings with a strength greater than 8% of the bottom-quark Yukawa coupling in the standard model can be excluded.

**Introduction.** The successful operation of the CERN Large Hadron Collider (LHC) and the ATLAS and CMS experiments have led to the discovery of the Higgs boson, the final piece of the standard model (SM) [1, 2] of particle physics. Future high precision experimental investigations on the couplings of the Higgs boson are required for a refined understanding of the nature of electroweak symmetry breaking and for searches for possible new physics beyond the SM. Higgs boson couplings can be measured to percent level precision at future lepton colliders, e.g., the International Linear Collider [3] and the Circular Electron-Positron Collider (CEPC) [4], or with less precision at the high luminosity run of the LHC (HL-LHC) [3]. In addition to high precision,  $e^+e^-$  colliders provide direct access to all possible decay channels of the Higgs boson, including invisible decays, in a clean environment. They can also measure the total width of the Higgs boson in a model-independent way.

An important prediction for the SM Higgs boson is that the couplings to other SM particles are proportional to their mass. It will be essential to test this relation experimentally. In the SM the Yukawa couplings of the Higgs boson to light quarks  $q$  ( $u$ ,  $d$ , or  $s$ ) are negligibly small due to smallness of their mass. There have been, however, theoretical models that have predicted enhanced light-quark Yukawa couplings [5, 6]. Experimentally, if such an enhanced-coupling scenario is observed, it will must indicate the presence of new physics; the quarks also receive masses from sources other than the Higgs boson in order to maintain a relatively small mass. However, a direct measurement of light-quark Yukawa couplings is impossible at hadron colliders due to the huge QCD backgrounds for hadronic decays of the Higgs boson. Indirect constraints can be obtained based on different kinematic distributions induced by gluon and quark production mechanisms [7–9] or through rare decays of the Higgs boson [10–14].

At lepton colliders, the main measurement difficulty is separation of the  $q\bar{q}$  decay channel from the loop-induced gluon channel, both of which generate similar final states of two untagged jets ( $jj$ ). In this Letter, we propose a novel idea of using hadronic event shape observables from the Higgs boson decays to separate  $q\bar{q}$  from  $gg$  channels

and to directly measure the light-quark Yukawa couplings at lepton colliders. Another possibility for lepton colliders involves utilizing discrimination of quark jets and gluon jets [15]. We leave this for future investigations. The idea is motivated by the measurement of the QCD coupling constant at LEP from hadronic event shape distributions. Intuitively, in that case the next-to-leading order QCD corrections,  $\sim \mathcal{O}(\alpha_s)$ , generate the distribution in three-jet region. A change of  $\alpha_s$  can induce changes of the event shape distributions, e.g., the position and height of the peak. Similarly, in the case of the Higgs boson decay, the real radiation is of  $\mathcal{O}(C_X\alpha_s)$ , where  $C_X$  is the QCD color factor, i.e.,  $C_A = 3$  for decay to gluons and  $C_F = 4/3$  for decay to quarks. Thus, a measurement of event shape distributions can reveal the average color factor and the ratio of decay branching ratios (BR) of the gluon and the quark channel.

In the remaining paragraphs we demonstrate theoretically how the distributions differ for quark and gluon channels, and we consider a scenario of the CEPC and demonstrate a precision of  $< 1\%$  can be achieved on the measurement of the decay BR to light quarks.

**Event shapes.** There have been 6 major observables of hadronic event shapes measured at LEP and used for the extraction of  $\alpha_s(M_Z)$ , including thrust  $T$  (or  $\tau = 1 - T$ ), heavy hemisphere mass  $M_H$ ,  $C$  parameter, total hemisphere broadening  $B_T$ , wide hemisphere broadening  $B_W$ , and the Durham 2 to 3-jet transition parameter  $y_{23}^D$  [16, 17]. For example, the thrust is defined as

$$T = \max_{\vec{n}} \left( \frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right), \quad (1)$$

where  $p_i$  is the three-momentum of particle  $i$  and the summation runs over all measured particles. One advantage of the global event-shape observables is that their distributions can be calculated systematically in perturbative QCD. In case of two-body hadronic decay, at the leading order (LO), the thrust distribution is a  $\delta$  function at  $\tau = 0$ . Finite thrust values are generated through high-order QCD radiations. Soft and collinear emissions introduce large logarithmic contributions  $\sim \alpha_s^n \ln \tau^{2n-1}/\tau$  at small- $\tau$ , the deep two-jet region.

They must be resummed to all orders in QCD to make reliable predictions, e.g., the state of art Next-to-Next-to-Next-to-leading logarithmic (N<sup>3</sup>LL) resummation [18–20] for  $Z/\gamma^* \rightarrow q\bar{q}$  in the extraction of  $\alpha_s(M_Z)$ . Meanwhile, in the three-jet region the resummed results can be further matched with the fixed-order results, e.g., the Next-to-Next-to-leading order (NNLO) calculation for  $Z/\gamma^* \rightarrow 3 \text{ jets}$  production [21, 22]. Usually, for calculations done at parton level, a correction factor due to hadronization effects needs to be applied when comparing to experimental data, which can be estimated through various event generators [23–26].

To our best knowledge, no predictions at comparable precision exist for hadronic decays of the Higgs boson, although most of the ingredients are already available. Predictions at N<sup>3</sup>LL+NNLO level for the Higgs boson are expected in near future. In this study, we calculate the event shape distributions using the MC event generator Sherpa 2.2 [26] with the effective coupling approach of the Higgs boson. We use the CKKW scheme [27], matching parton showers with tree-level matrix elements with up to three jets, which is effectively partial next-to-leading-logarithmic and leading-order accuracy. The hadronization corrections are included automatically in this case through a hadron-level simulation.

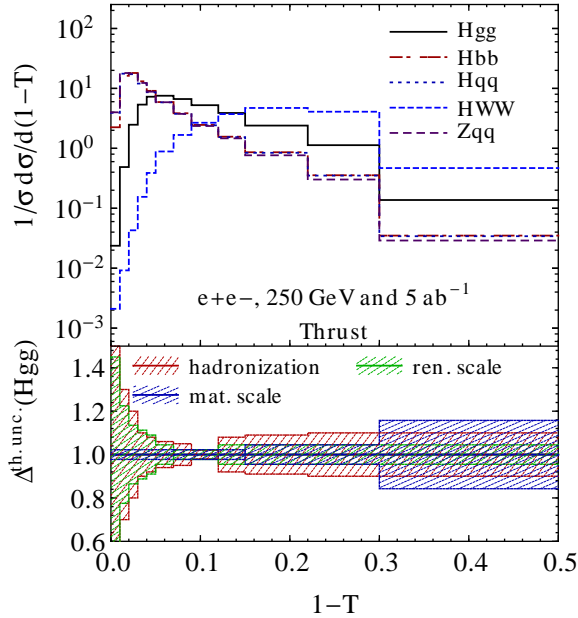


FIG. 1. Normalized distributions of the thrust in hadronic decays of the Higgs boson, and of  $Z^*/\gamma^* \rightarrow q\bar{q}$ , with a center-of-mass energy of 125 GeV. The lower panel shows the relative theoretical uncertainties of the normalized distribution for  $H \rightarrow gg$ , including the renormalization and matching scale variations, and the uncertainty on hadronization corrections.

Fig. 1 shows the normalized distribution of the variable thrust for several different hadronic decay channels of the

Higgs boson, including  $gg$ ,  $q\bar{q}$ ,  $b\bar{b}$ , and  $W(q\bar{q})W^*(q\bar{q})$ . We also plot the distribution for  $Z^*/\gamma^* \rightarrow q\bar{q}$  as a comparison. The distribution peaks at  $\tau \sim 0.02$  for light-quark decay channel. The peak shifts to  $\tau \sim 0.05$  for the gluon channel, corresponding to a scaling of roughly  $C_A/C_F$ . The distribution is much broader for the gluon case due to the stronger QCD radiation. The distribution for the  $b\bar{b}$  channel is very close to the  $q\bar{q}$  case, except at very small  $\tau$ , where the mass and hadronization effects become important. For the  $WW^*$  channel there exist already four quarks at LO and the distribution is concentrated in the large- $\tau$  region. The distribution for  $q\bar{q}$  from  $Z^*/\gamma^*$  differs from that for the Higgs boson in the three-jet region because of the different spin.

In the lower panel of Fig. 1, we plot the estimated theoretical uncertainties of the normalized thrust distribution for the decay to gluons. The hadronization uncertainties are estimated according to [28] where hadronization corrections from different event generators are compared. There are also theoretical uncertainties due to the truncation of the perturbation series that are conventionally estimated through QCD scale variations. These include variations due to the change of the renormalization scale and the matching scale [29]. The latter variation mostly affects the distribution in the large- $\tau$  region. As one includes higher-order resummation and fixed-order matching contributions, the scale variations will decrease. We assume a N<sup>3</sup>LL+NNLO calculation for the Higgs boson decay to gluons will be available and estimate the scale variations based on the calculation for  $Z/\gamma^*$  [18, 28] using a scaling factor of  $C_A/C_F$ . Since the distribution is normalized, the uncertainties are small in the peak region. The uncertainty due to the  $\alpha_s(M_Z)$  input is negligible if the world average [30] is used. Below, we will discuss the possibility of measuring the distributions discussed above at a lepton collider and the sensitivity of these measurements to the light-quark Yukawa couplings.

**CEPC.** A circular electron-positron collider has been proposed recently with a center-of-mass energy of 250 GeV and a total integrated luminosity of  $5 \text{ ab}^{-1}$  [4]. It can serve as a Higgs factory with the dominant production channel being the associated production with a  $Z$  boson, with a total cross section of about 212 fb [31]. One great advantage of the  $e^+e^-$  collider is that the Higgs boson events can be selected by measuring the recoil mass  $m_{\text{recoil}}$ , e.g., for  $ZH$  production with the  $Z$  boson decay into a pair of visible fermions  $f\bar{f}$ ,

$$m_{\text{recoil}}^2 = s - 2E_{f\bar{f}}\sqrt{s} + m_{f\bar{f}}^2, \quad (2)$$

where  $E_{f\bar{f}}$  and  $m_{f\bar{f}}$  are the total energy and invariant mass of the fermion pair. The recoil mass spectrum should present a sharp peak at the Higgs boson mass. The Higgs boson events can be selected with a high signal to background ratio independent of the decay modes

$Z(l^+l^-)H(X)$	$gg$	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
$BR$ [%]	8.6	57.7	2.9	9.5	1.3	$\sim 0.02$
$N_{event}$	6140	41170	2070	6780	930	14

TABLE I. The decay branching ratios of the SM Higgs boson with a mass of 125 GeV to different hadronic channels [32] and the corresponding expected numbers of events in  $ZH$  production, with subsequent decays at a  $e^+e^-$  collider with  $\sqrt{s} = 250$  GeV and an integrated luminosity of  $5 \text{ ab}^{-1}$ . Only decays of the associated  $Z$  boson to electrons and muons are included.  $h$  represents any of the quarks except the top quark and  $q$  are light quarks.

of the Higgs boson. Using the kinematic information of the recoil system, we can boost all decay products back to the rest frame of the Higgs boson and measure the event shape distributions in that frame.

Table I summarizes the decay BRs of the hadronic decays of the SM Higgs boson and the expected numbers of events at the CEPC through  $ZH$  production, with the  $Z$  boson decaying into electron or muon pairs. As one can see, the  $q\bar{q}$  (light quarks) channel is negligible in the case of the SM Higgs boson. All the hadronic channels in Table I contribute to the distribution of the event shapes. We must carefully select the one that we are interested in, which is the  $jj$  ( $gg+q\bar{q}$ ) channel. To suppress the heavy-quark contributions, one can use flavor tagging of the heavy quarks,  $b$  and  $c$ , a technique which is well established at hadron and lepton colliders [33]. It has been shown that, assuming an efficiency of 97.2% for identification of gluon or light quarks  $j$ , the misclassification rate of a  $b$  or  $c$  quark to  $j$  at CEPC could reach 8.9% and 40.7% respectively [4, 34]. Since there are two quarks/gluons from the decay, by requiring both of them untagged one can remove 99(84)% of the  $b\bar{b}(c\bar{c})$  background while only changing the signal  $jj$  by 6%. There are also backgrounds from other SM processes, especially from the SM  $Z$  boson pair production, which have a flat distribution in the recoil mass. After applying further selection cuts, e.g., on recoil mass, dilepton mass, and the polar angle of the Higgs boson, we estimate a total signal ( $jj$ ) efficiency of 50% [4, 31]. We assume a total  $q\bar{q}$ -like background of 30% of the signal rate from Higgs boson decays to  $b\bar{b}$ ,  $c\bar{c}$  and the SM  $ZZ$  production. A second category of backgrounds are from decays to  $WW^*$ ,  $ZZ^*$  and further to four quarks. Since they are away from the peak region of our signal, as shown in Fig. 1, they do not have a large impact to the measurement of the light-quark couplings. We estimate a total rate of 60% of the signal for these four-quark backgrounds after all selection cuts. They can be further suppressed if additional cuts on dijet masses are used.

Including both the signal and backgrounds, the event shape distributions at hadron level can be expressed as

$$\frac{dN}{dO} = N_S(r f'_{q\bar{q}}(O) + (1-r) f_{gg}(O))$$

$$+ N_{B,1} f'_{q\bar{q}}(O) + N_{B,2} f_{WW}(O), \quad (3)$$

where  $N_S$ ,  $N_{B,1}$ , and  $N_{B,2}$  are the expected number of events for the signal, the  $q\bar{q}$ -like background and the four-quark background, respectively. We normalize the signal rate to the SM result,  $N_S = \lambda N_{S,SM}$  with  $\lambda = \sigma(HZ)BR(jj)/\sigma(HZ)BR(jj)_{SM}$ . From previous discussions, we have  $N_{S,SM} = 3070$  and  $N_{B,1} = N_{B,2} = 0.3N_{S,SM}$ . In addition,  $r = BR(q\bar{q})/BR(jj)$  is the fraction of the Higgs boson BR to light quarks which we would like to measure. Both  $r$  and  $\lambda$  allow possible deviations from the SM which has  $r = 0$  and  $\lambda = 1$ . In Eq. (3)  $f_{q\bar{q}/gg/WW}$  is the normalized distribution of the Higgs boson decay to light quarks, gluons, or four quarks through  $W$  boson pairs as shown in Fig. 1.  $f'_{q\bar{q}}$  is a mixture of the normalized distributions  $f_{b\bar{b},c\bar{c}}$  and the one from  $Z^*/\gamma^*$  decay  $f_Z$ . We set  $f'_{q\bar{q}} = f_{q\bar{q}}$  for simplicity since all of the above components are very similar. In principle, all of  $f_{b\bar{b}\sim q\bar{q},Z,WW}$  can also be measured directly from independent data samples with high statistics. We do not consider any theoretical uncertainties of  $f_{q\bar{q},WW}$  and  $f'_{q\bar{q}}$  in the discussions below. Since most of the selection cuts do not alter the hadronic system, they are not expected to change the normalized distributions greatly especially for the signal.

We further investigate the sensitivity of the proposed measurement to the light-quark Yukawa couplings using pseudo-data. To be specific, we study the expected exclusion limit on  $r$ , as a function of  $\lambda$ , assuming the decay to  $q\bar{q}$  vanishes. We take into account 6 systematic uncertainties for the thrust distribution. Three of them are the theoretical uncertainties of the normalized distribution for the decay to  $gg$ , as shown in Fig. 1, (anti-)correlated among all bins. The other three are for the normalization of the signal and the two backgrounds in Eq. (3). Normalization uncertainties on both of the backgrounds are set to 4%. Normalization of the signal can be measured independently using hadronic decays of the  $Z$  boson in  $ZH$  production with the Higgs boson decay to  $jj$ , and the uncertainty is estimated to be 3% [4]. Systematic uncertainties are treated using nuisance parameters. Statistical errors are included according to the assumed event rates. We use the profiled log-likelihood ratio  $q_\mu$  as our test-statistic [35], together with the CL<sub>s</sub> method [36]. Fig. 2 shows the expected 95% CL<sub>s</sub> exclusion limit on  $r$  (in the dashed line) from the thrust distribution. The colored bands indicate the  $1\sigma$  and  $2\sigma$  fluctuations of the expected exclusion limit. In case the true theory is the SM, the expected exclusion limit on  $r$  can reach 0.045, which is the intersection of the curve and the vertical line. That corresponds to a decay BR of 0.39% to  $q\bar{q}$ . In term of the Yukawa coupling strength, that implies  $y_q < 0.082y_b$  for any of  $q = u, d, s$ , with  $y_b$  being Yukawa coupling of the bottom quark in the SM. The discrimination power for  $q\bar{q}$  and  $gg$  is mostly determined by the statistical error. In principle, we can also include invis-

ible decays of the associated  $Z$  boson in the analysis. They have a total rate 3 times larger than to electrons and muons and suffer from a relatively larger  $ZZ$  background due to a degradation of the signal-background separation power from the recoil mass. Thus, we simply assume that once the  $\nu\nu$  channels are included, both the signal and backgrounds will double. The expected limit is again plotted in Fig. 2, which can reach 0.036 with the SM assumption.

Similar exclusion limits can be set based on other event shape observables which are summarized in Fig. 3. Here, only the statistical error and the systematic uncertainty on the signal and background normalizations are included in the analysis, since the estimation of scale variations on some of the distributions is not available at the  $N^3\text{LL}+\text{NNLO}$  level. We can judge that the theoretical uncertainties on the distribution are not the major limitation on the measurement by comparing results for thrust distribution in Figs. 2 and 3. The binnings used in the analysis for all other distributions are chosen to be the same as in Ref. [37]. All distributions show a similar sensitivity to the light-quark Yukawa couplings except for the Durham 2 to 3-jet transition parameter  $y_{23}^D$ , which is slightly worse, possibly due to binning effects.

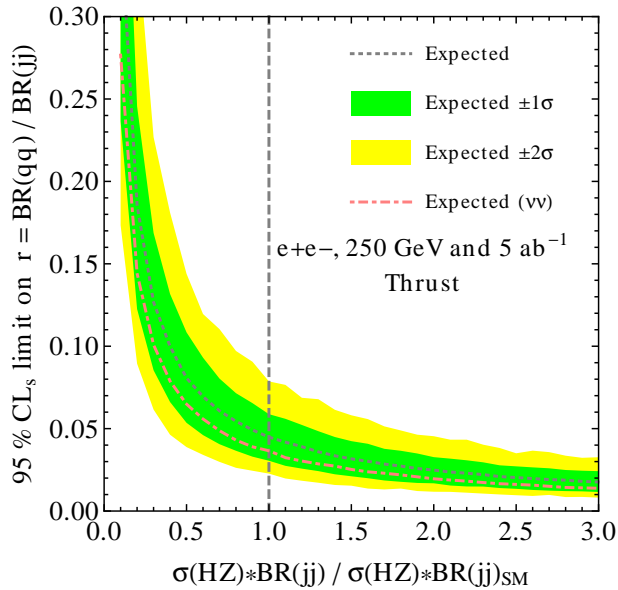


FIG. 2. Expected 95%  $\text{CL}_s$  exclusion limit on  $r$  and the  $1\sigma$  and  $2\sigma$  fluctuations as a function of the total cross section of the Higgs boson decay to  $jj$  normalized to the SM value. The dot-dashed line is the expected exclusion limit when invisible decays of the  $Z$  boson are also included in the analysis.

**Discussion and summary.** It is interesting to compare our sensitivity to the light-quark Yukawa couplings with the projection of the LHC and HL-LHC. Ref. [9] claims an expected 95% CL limit of the Yukawa couplings

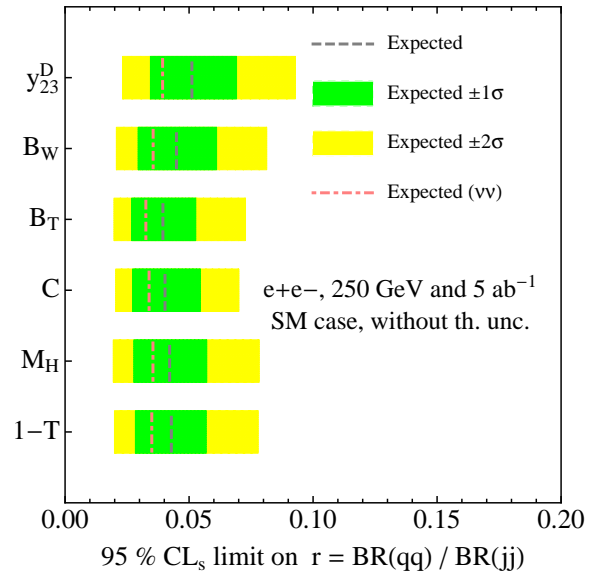


FIG. 3. Expected 95%  $\text{CL}_s$  exclusion limit on  $r$  and the  $1\sigma$  and  $2\sigma$  fluctuations based on measurements of different event shape observables and assuming a theory of the SM. Theoretical uncertainties on the event shape distributions are not included.

$y_{u,d} < 0.4y_b$ , for LHC 13 TeV run with a total luminosity of  $300 \text{ fb}^{-1}$ , based on analyzing the  $p_T$  distribution of the Higgs boson. Ref. [8] reports a sensitivity of  $y_s \sim 0.52y_b$  for the strange quark at the HL-LHC. Comparing with results above, our method does not only provide a much stronger sensitivity of  $y_{u,d,s} < 0.082y_b$  (95%  $\text{CL}_s$ ) but also probes the light-quark couplings directly and in a model-independent way. The major limitation on probing the light-quark Yukawa couplings at the LHC/HL-LHC is that the  $gg$  parton luminosity is much larger than the  $q\bar{q}$  ones for a Higgs boson mass of 125 GeV. Thus, a small downward shift of the  $gg$  induced cross sections comparing to experimental data, either due to the experimental or theoretical uncertainties, can allow for a much larger light-quark Yukawa coupling.

We also comment on the comparison of our proposal with the possibility of using gluon/quark jet discriminators. On the theory side, the event shape distributions can be calculated systematically in perturbative QCD, and the theoretical uncertainties are under control. Experimentally, the hadronic even-shape observables have been studied extensively at LEP. The experimental systematics are well understood. By comparing with the experimental results on the  $\alpha_s(M_Z)$  measurement [37, 38], we found the sensitivity obtained in this study is realistic. Even after all the experimental systematics are included, the expected exclusion limit should not change greatly.

In summary, we have proposed a novel idea for measuring the light-quark Yukawa couplings using hadronic event shape distributions at lepton colliders. We show that for a  $e^+e^-$  collider with a center-of-mass energy of



250 GeV and an integrated luminosity of  $5 \text{ ab}^{-1}$  one can expect to exclude a decay BR of 0.39% for the Higgs boson decay to  $q\bar{q}$ , at 95% CL<sub>s</sub>, with  $q$  be any of the  $u, d, s$  quarks. That corresponds to an exclusion limit on a light-quark Yukawa coupling of about 8% of the strength of the bottom quark coupling in the SM.

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